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NATIONAL BUREAU OF STANDARDS REPORT

9614

EFFECT OF SOME HARDENING VARIABLES ON THE MECHANICAL PROPERTIES OF TYPE 431 STAINLESS STEEL

By

I. J. Feinberg
Engineering Metallurgy Section

To

Materials Division
Air Systems Command
Department of the Navy

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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U. S. DEPARTMENT OF COMMERCE
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Effect of Some Hardening Variables on the Mechanical Properties of Type 431 Stainless Steel

Introduction: Type 431 stainless steel is a complex alloy that requires exacting care from the melting stage through the final clean-up of part surfaces to attain the properties of which the alloy is capable. When fully hardened to 200,000 psi minimum tensile strength it offers the best corrosion resistance of all the hardenable stainless steels. However, when improperly processed it may be extremely brittle and susceptible to intergranular corrosion.

Angstadt and Gassner, who have worked extensively with this alloy, have traced some difficulties to faults in the hardening practice.(1) The Naval Air Systems Command suspects that part failures it has experienced stem from this source. At the request of that agency studies have been conducted to determine the effects of air quenching, oil quenching and refrigeration and the effects of different types of atmospheres and of delays before quenching on the mechanical properties of type 431 stainless steel. These studies were concerned exclusively with material of small diameter, heat treated to 200 Ksi minimum ultimate tensile strength.

Material: The test material obtained for this investigation was 0.625 inch diameter bar stock. This size was used inasmuch as many of the hardening problems that have been encountered are in components that have a section diameter of 0.50 inch or less.

All of the bar stock originated from a single heat. The chemical composition in weight percent as determined by the Analytical Chemistry Division of the National Bureau of Standards for elements other than iron was as follows: 0.152 carbon, 0.7 manganese, 0.5 silicon, 0.018 phosphorus, 0.019 sulfur, 2.3 nickel, 15.5 chromium, 0.2 molybdenum and 0.044 nitrogen. The chemical composition of the steel complied with that specified for type 431 in Mil-S-18732 C. This document specifies a range of 15.50 - 17.00 percent chromium for 431. The chromium content of the test material used in these investigations is the lower limit of this range. The hardness of the material as-received averaged 235 Brinell ($\approx$ Rockwell$_B$ 99).

Samples of the test steel in the as-received condition were examined metallographically. The microstructures are shown in figures 1 and 2. The inclusion content, figure 1, appears to be greater than that expected in steel of aircraft quality. The as-received annealed microstructure shown in figure 2 consists of ferrite, decomposition products of austenite and some austenite.

(1) C. C. Angstadt and R. H. Gassner, Douglas Materials and Process Engineering Report, E.S.R. 50514, May 14, 1955.

Section I. Effects of Quenching Media and Refrigeration

Objectives: Air quenching is a slow quench and oil quenching a moderately fast one. Equivalent hardnesses have been obtained in hardening type 431 stainless steel parts by either quench method. Refrigeration is introduced into type 431 heat treating cycles to reduce residual austenite contents. The lowered retained austenite is thought desirable to limit the possibilities of embrittlement and unacceptable dimensional changes resulting from temperature fluctuations in service. Questions as to the suitability of an air quench and the refrigeration treatment in heat treating small type 431 parts to a tensile strength of 200 Ksi have led to this investigation in which properties obtained by air quenching and oil quenching, both with and without refrigeration in the heat treating cycle, are compared.

Specimens and Procedure: Tensile and impact test specimens for the study of air and oil hardening and refrigeration effects were machined 0.040 inch oversize before heat treatment. The specimens were divided into four groups for heat treatments, designated as A, B, C and D. The heat treatment sequence for each group is given in figure 3. After heat treatment specimens were ground to finished dimensions and then tested.

Results and Discussion: Tensile and Charpy V-notch impact properties obtained after subjecting the test material to heat treatments A, B, C and D are presented in figure 4. It is evident from these data that although type 431 can be heat treated to a tensile strength of 200 Ksi by a heat treatment involving either an air quench or an oil quench generally higher mechanical properties are obtained through oil quenching than through air quenching. The variations in the heat treatments had little effect on hardness. Refrigeration reduced the yield strength of both air quenched and oil quenched material and conversely increased the ultimate tensile strength. Through elimination of refrigeration the ratio of yield strength to ultimate tensile strength was increased. The removal of refrigeration from heat treating sequences employing either an air quench or an oil quench slightly improved ductility (percent elongation and reduction of area) and markedly improved Charpy V-notch impact properties at both room temperature and -40° F.

Heat treatment of the 431 test material by sequence D, involving a stabilization treatment, austenitizing in air, quenching in oil and a double temper yielded the best combination of tensile properties and Charpy V-notch impact strength. The superior ductility and V-notch impact properties of this material were evidently imparted by a relatively high residual austenite content. Through X-ray determinations retained austenite contents were found to be as follows:

Sequence	Retained Austenite, volume %
A	< 3
B	18
C	< 3
D	10

Retained austenite or ferrite banding was not observed in the structure of the sequence D material or in the structure of the other test materials. Changes in microstructure resulting from the variations in the heat treatment employed are subtile and not readily revealed with an optical microscope. Consequently, the quenched and tempered martensitic structures obtained after the four heat treatments are all similar in appearance, figure 5.

Conclusions: Higher tensile and notch impact properties are obtained by quenching type 431 stainless steel in oil than by air quenching. In this investigation a type 431 heat treating sequence that included a stabilization heat treatment, austenitizing in air, quenching in oil and a double temper yielded the best combination of tensile properties and notch toughness. This heat treating sequence, basically, was used in the other studies herein reported.

A residual austenite content of 10% obtained in a heat treatment involving oil quenching and tempering (minus refrigeration) is not excessive and is beneficial to this steel. Refrigeration to reduce retained austenite contents lowered the ductility (percent elongation and reduction of area) of the material slightly. It reduced notch toughness markedly. Refrigeration is definitely not recommended for this steel.

Section II. Effects of Heat-Treating Atmospheres

Objectives: Austenitizing atmospheres vary in their capacity to prevent minimize or control changes on the surface of work being hardened. Surface condition has an effect on some of the mechanical properties of metals. This study was conducted to determine the changes effected by air, argon, dissociated ammonia, endothermic gas, exothermic gas, hydrogen, nitrogen and vacuum on the surface of type 431 stainless steel in hardening and the effects on tensile and V-notch Charpy impact properties resulting from these changes.

Specimens and Procedure: 0.5 inch diameter by 4.0 inch specimens were used in determining the effects of atmospheres on material surfaces. The specimens were austenitized in these atmospheres and oil quenched. The carbon, nitrogen, oxygen and hydrogen contents of a surface layer 0.03 inch deep on the specimens were then determined. Carbon was determined by the combination-gravimetric method; nitrogen, oxygen and hydrogen by the vacuum-fusion method. The hardness of the 0.03 inch deep surface layer and the hardness of the core of the specimens were also ascertained.

ASTM standard longitudinal tensile test specimens with a 1.0 inch gage length and 0.252 inch diameter in the reduced section and standard Charpy V-notched impact test specimens were used in determining the effects of austenitizing atmospheres on mechanical properties. These specimens were

ground to size before heat treatment so that the affected surface layer would not be removed by a post heat treatment finish machining. The following heat treating sequence was employed:

Heat Treating Sequence used in Study of Effects of Atmospheres

Stress relieve 1/2 hour at 1200° F;
air cool.

Austenitize in subject atmospheres, 1/2 hour
at 1900° F.

Quench rapidly in oil at 100 - 105° F. Then
cool to room temperature in cold water.

Temper twice for 2 hours, each temper at 550° F;
air cool.

The mechanical test specimens were tested with the heat treated surfaces intact.

Austenitization in exothermic gas was effected at a dew point of 100° F, the optimum temperature employed by a commercial vendor. Austenitization in the other gaseous media was effected at the highest dew point temperature and at the lowest dew point temperature consistent with a given atmosphere and available equipment. The austenitizing media used and their dew points are included in table 1.

Results and Discussion: All of the hardening treatments (austenitizing and oil quenching) produced a discolored film or even mild scaling effect on material surfaces. Characterized as to product, the film or scale ranged from the light yellowish tarnish produced by hydrogen dew point temperature (D.P. -17° F) to a blue-black deposit produced by hydrogen (D.P. -87° F). All surface effects were thin and adherent.

Table 1 gives the interstitial contents of the 0.030 inch surface layer on specimens after hardening. It shows the extent to which interstitial changes to a depth of 0.030 inch beneath the surface varied with the atmosphere and the atmosphere dew point temperature employed in hardening. Argon (D.P. -76° F) controlled the alteration of surface interstitial contents best, as shown by the only very slight changes in interstitial content after treatment. Good control was also obtained with endothermic gas (D.P. 72° F), air (D.P. -30° F) and nitrogen (D.P. -80° F). It is

noteworthy that better results were obtained when argon, air and nitrogen were dry rather than wet. Poor control of surface interstitial contents resulted from the use of dissociated ammonia (wet or dry), endothermic gas (D.P. 13° F), exothermic gas (D.P. 100° F), hydrogen (wet or dry) and vacuum.

Figures 6 through 13 show the microstructures of type 431 adjacent to the surface after the various hardening treatments. Some peripheral areas appear unaffected while cases present in others are evidence that metallurgical changes have occurred. Dissociated ammonia (D.P. -59° F) and hydrogen (D.P. -87° F and -17° F) produced decarburized cases. Endothermic gas (D.P. 13° F) and the vacuum-oil quench treatment produced carburized cases. The cases were probably formed through the reaction of the gaseous media with the material surfaces during austenitization. The thin case formed on the vacuum treated material is believed to be due to the reaction of the hot metal surface with the oil during the quench.

Changes in hardness revealed by hardness traverses confirmed that some metallurgical change occurred adjacent to the surface of all of the austenitized material, table 2. Low hardnesses found to a depth of 0.0015 inch are probably associated with the reduced total of carbon plus nitrogen found in all but one of the samples.

The tensile properties of the finish machined type 431 test material, austenitized in the various media and fully heat treated are given in figures 14 and 15. Charpy V-notch impact properties are given in figure 16. These data indicate that austenitizing atmospheres varied little in their effects on tensile strength, yield strength, percent elongation and reduction of area. Effects on tensile properties were found to be inconclusive. This is probably due to the insensitivity of these properties to subtile changes in surface conditions. However, notch toughness at both room temperature and at -40° F are greatly influenced by the austenitizing atmosphere employed. There is a correlation between the capacity of an atmosphere to control surface alteration during austenitization and notch toughness properties obtained. Generally, good notch toughness properties were linked with a low alteration of surface interstitial contents. Good combinations of tensile and notch toughness properties were obtained from material austenitized in air and in argon which afforded good control. Inferior combinations of these properties were obtained from material austenized in dissociated ammonia, endothermic gas, hydrogen and nitrogen which rendered relatively poor control. A good combination of properties was obtained after austenitization in vacuum. The case formed in the vacuum austenitizing treatment apparently had little effect on tensile properties or notch toughness.

High yield strengths and ultimate tensile strengths were obtained by austenitizing in dissociated ammonia, endothermic gas, hydrogen and nitrogen. However, notch toughness obtained in these treatments was generally low. No appreciable improvement in notch toughness resulted from austenitization in dry dissociated ammonia or in dry endothermic gas.

Austenitization in dry hydrogen and in dry nitrogen resulted in very low -40° F notch impact values. On the other hand austenitization in dry air and in dry argon improved low temperature notch toughness.

Conclusions: Protection of the surface of type 431 stainless steel from alteration of its original interstitial contents is necessary to avoid poor ductility and toughness. No over-all improvement in properties is obtained by austenitizing in dry dissociated ammonia, dry hydrogen or dry nitrogen, but better properties are obtained after austenitizing in dry air and in dry argon. Considering combined effects on tensile properties and notch toughness the atmospheres investigated are rated as follows:

Good	Fair	Poor
Air (D.P. -30° F)	Argon (D.P. -38° F)	Air (D.P. 70° F)
Argon (D.P. -76° F)	Exothermic gas (D.P. 100° F)	Dissociated ammonia (D.P. -59° F)
Vacuum	Hydrogen (D.P. -17° F)	Dissociated ammonia (D.P. 24° F)
	Nitrogen (D.P. -18° F)	Endothermic gas (D.P. 13° F)
		Endothermic gas (D.P. 72° F)
		Hydrogen (D.P. -87° F)
		Nitrogen (D.P. -80° F)

Section III. Effects of Delays Before Quenching

Objectives: Delays or variations in the interval between austenitizing and quenching can occur in all steel hardening operations from mechanical deficiencies and from negligence on the part of heat treaters. There is scant information on the effects of delays before quenching on type 431 stainless steel. This study was conducted to determine the effects of delays of up to one minute between removal from the furnace and quenching on the microstructure, tensile and Charpy V-notch impact properties of this alloy.

Specimens and Procedure: Specimens 0.187 inch and 0.50 inch in diameter and 1.00 inch in length were used to obtain cooling rate data for the study of the effects of delays before quenching. Holes 0.375 inch deep were drilled in one end of these specimens to accommodate a sheathed AWS 30 gage chromel-alumel thermocouple. The couple was monitored by a potentiometer recorder for temperature-time measurement. The delay time established was the time elapsed in transferring specimens from the furnace mouth to an oil bath.

Tensile and impact test specimens for this study were machined 0.040 inch oversize before heat treatment. After stress relief and austenitization these specimens were subjected to 1, 9, 15, 30 and 60 second delays before quenching. The full heat treatment given was one that yielded a good combination of mechanical properties in a related investigation. The full heat treatment was as follows:

Heat Treating Sequence Used in Study of Effects of Delays Before Quenching

Stress relieve 1/2 hour at 1200° F; air cool.

Austenitize in air, 1/2 hour at 1900° F

Quench in oil at 100 - 105° F after delays. Then cool to room temperature in cold water.

Temper twice for two hours, each temper at 550° F; air cool.

After heat treatment, the tensile and impact test specimens were ground to finished dimensions and then tested.

Results and Discussion: When cooling rate study specimens were drawn to the furnace mouth, where they were delayed before quenching, there were immediate drops from the austenitizing temperature (1900° F) to the temperatures shown at zero time, figure 17. The 0.187 inch diameter specimens cooled to lower temperatures than the 0.50 inch diameter specimens. Delay intervals resulted in corresponding increases in the time occupied in an ensuing slow cooling stage for both sizes. During the delays the larger specimens cooled much more slowly than the smaller. On quenching, specimens of both sizes cooled to 1000° F at fast and surprisingly similar rates, figures 18 and 19.

The effects of mass in causing the smaller specimens to cool to lower temperatures at zero delay time are obvious. However, the much slower cooling of the larger specimens during respective quench delays cannot be attributed to mass alone. The greater amount of heat liberated on the precipitation of non-martensitic products in the high temperature transformation of austenite during quench delays contributed to the slower cooling of the larger specimens. It is apparent from these data that quench delays retard the cooling rate and prolong the precipitation of the non-martensitic products.

According to Angstadt and Gassner(2) carbides are precipitated from austenite in type 431 at 1400° F after 12 seconds at that temperature. Using this reaction temperature and the cooling rates in table 3 as criteria it would seem quench delays as long as 60 seconds could be tolerated in hardening 0.187 inch diameter material before carbide precipitation occurred; but delays should be limited to about 7 seconds to avoid carbide precipitation in 0.50 inch diameter material.

In examining microstructures it was found that appreciable carbide precipitation resulted from a 12 second delay before quenching in both sizes, figures 20 and 21. From this it is apparent that the condition of the material prior to hardening may also influence carbide precipitation. Or it is possible that some of the carbides in the microstructure of specimens subjected to short quench delays are the residue of a prior heat treatment, not having been completely dissolved in austenitization for these tests. It is very difficult to obtain a type 431 quenched and tempered martensitic structure free of carbides. Nevertheless, it is apparent from this investigation that carbide precipitation in type 431 is influenced to a large degree by quench delays; and that quench delays should be as short as possible for carbide control.

Banding of carbides such as that obtained after 60 second quench delays is particularly detrimental to material properties. Carbides thus formed

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(2) From isothermal transformation diagram, page 22, reference (1).

usually have a high chromium content ($Cr_{26}C_6$). They induce brittleness and because they deplete the chromium content in surrounding areas in the structure they may reduce corrosion resistance.

Interestingly, varying quench delays had little effect on the quenched and tempered martensitic structures obtained in heat treatment. The structures revealed by etching and observed microscopically after quench delays of from 1 to 60 seconds, were similar in appearance, figures 22 and 23. Ferrite was not observed to any appreciable extent.

Hardness: Hardness obtained at the periphery, mid-radius and center of specimens subjected to quench delays are given in table 4. The Rockwell C values listed are approximate equivalent conversions from Superficial Rockwell 45 N. Low hardness values found at the periphery of some of the test material is attributed to decarburization. At mid-radius and center hardness ranged from 42 to 46 Rockwell C. The higher hardnesses, 45 and 46 Rockwell C, obtained at mid-radius and at the center of the 30 and 60 second delay specimens are attributed to the precipitation of the carbides previously noted. Neglecting instances of low peripheral hardness, the data in table 4 generally show through hardening regardless of the delay interval.

Mechanical Properties: Tensile property data given in table 5 indicate that yield strength and ultimate tensile strength are similar after quench delays of up to 30 seconds and only a small decrease in these properties occurs when the material is subjected to a 60 second quench delay. Percent elongation and reduction of area generally increased slightly as the delay interval was increased. The similarity in tensile properties is not surprising in view of the likeness in microstructure obtained throughout the delay spectrum.

Charpy V-notch impact data given in table 6 indicate there is no appreciable effect on fracture toughness at ambient temperature from quench delays of up to 15 seconds; but delays of 30 and 60 seconds result in slightly higher fracture toughness at these temperatures. Conditioning of specimens at -40° F to induce brittleness reduced the notch toughness of all quench delay material. The greatest reduction occurred in specimens quenched after 30 and 60 second delays.

Conclusions: Detrimental carbide precipitation in type 431 stainless steel will result from extended delays before quenching. Quench delays appear to have a greater effect than mass in retarding the rate of cooling of material of small size. They should be as short as possible to minimize the possibility of serious carbide precipitation.

Hardness and tensile property tests alone may be misleading in determining the quality of type 431 after heat treatment since harmful carbide precipitation will not show up in these tests. Charpy V-notch impact tests at -40° F and specific metallographic examination are suggested to detect this condition.

Table 1. Interstitial Contents of Surface Layers on Type 431 Stainless Steel Specimens Hardened from Various Austenitizing Media (Depth of Surface Layer 0.030 Inch)

Specimen	Austenitizing Medium	Dew Point Temp.	Carbon	Nitrogen	Oxygen	Hydrogen	Carbon + Nitrogen
		F	%	%	%	%	%
As-Received Material	-	-	0.152	0.044	0.011	0.0003	0.196
D-10	Air	- 30	0.155	0.026	0.015	0.0004	.181
D-11	Air	70	0.150	0.021	0.015	0.0004	.171
D-12	Argon	- 76	0.149	0.045	0.014	0.0003	.194
D-13	Argon	- 38	0.148	0.032	0.018	0.0004	.180
D-20	Dissociated ammonia	- 59	0.127	0.049	0.013	0.00035	.176
E-19	Dissociated ammonia	24	0.138	0.043	0.021	0.0035	.181
D-17	Endothermic gas	13	0.224	0.045	0.023	0.0003	.269
D-16	Endothermic gas	72	0.150	0.042	0.017	0.0003	.192
D-6	Exothermic gas	100	0.132	0.029	0.053	0.00055	.161
E-20	Hydrogen	- 87	0.135	0.043	0.011	0.0005	.178
D-3	Hydrogen	- 17	0.126	0.025	0.015	0.00045	.151
D-14	Nitrogen	- 80	0.153	0.037	0.015	0.0003	.190
D-15	Nitrogen	- 18	0.147	0.033	0.013	0.0003	.180
D-8	Vacuum[1]	-	0.165	0.025	0.011	0.00035	.190

[1] 190 microns for 1/2 hour at 1900° F.

Table 2. Rockwell C Hardness of Type 431 Stainless Steel Specimens After Various Austenitizing Treatments.[1]

Austenitizing Medium	Dew Point Temp.	Approximate Rockwell C Hardness of Surface Layer at Various Depths				
		0.0 - 0.0015"	0.0015 - 0.01"	0.01 - 0.02"	0.02 - 0.03"	Center
	F					
Air	- 30	44	48	48	47	45
Air	70	41	47	47	46	46
Argon	- 76	42	46	47	45	45
Argon	- 38	42	46	46	46	46
Dissociated ammonia	- 59	43	47	46	44	42
Dissociated ammonia	24	42	47	45	46	44
Endothermic gas	13	43	45	43	44	45
Endothermic gas	72	44	47	47	47	44
Exothermic gas	100	42	47	46	46	44
Hydrogen	- 87	37	47	48	48	46
Hydrogen	- 17	42	45	48	48	52
Nitrogen	- 80	39	47	46	46	48
Nitrogen	- 18	43	47	45	45	44
Vacuum	-	35	45	45	46	46

[1] Rockwell C hardnesses are approximate equivalent conversions from Knoop values obtained with a 500 gram load.

Table 3. Cooling Rates from 1900° F to 1400° F of Type 431 Test Material Subjected to Intervening Quench Delays

Quench Delay, Sec.	Cooling Rate, Deg. F/Sec. 0.187 in. Dia.	 0.50 in. Dia.
1	272	93
4	104	65
6	71	51
9	59	39
12	50	32
15	45	29
30	45	17
60	45	17

Table 4. Hardness of Fully Heat Treated Specimens Quenched after Various Delays

Quench Delay, Sec.	Rockwell C Hardness[1] 0.187 in. Dia.			0.50 in. Dia.		
	P[2]	MR[3]	C[4]	P	MR	C
1	40	45	44	44	44	44
4	44	43	44	43	45	44
9	39	42	43	43	45	43
15	44	44	45	37	45	44
30	43	45	45	41	45	46
60	45	45	46	38	46	45

[1] Rockwell C values are approximate equivalent conversions from Rockwell 45 N.

[2] Periphery

[3] Mid-radius

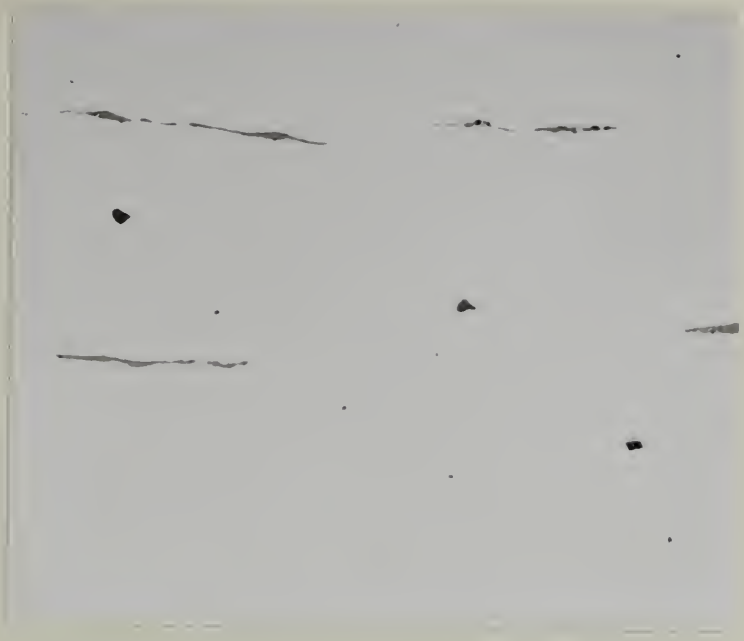
[4] Center

Table 5. Tensile Properties of Fully Heat Treated Type 431 Test Material Subjected to Intervening Quench Delays. Results from Longitudinal Test Specimens Heat Treated and then Ground to Finished Dimensions Before Testing. (Average of 4 Specimens)

Quench Delay, Sec.	0.2% Yield Strength, Ksi	Ultimate Tensile Strength, Ksi	Elongation in 1 Inch, Percent	Reduction of Area, Percent
1	143.25	203.25	17.7	52.7
9	142.75	204.25	18.1	55.3
15	144.50	204.75	18.3	58.3
30	142.50	204.25	18.3	59.3
60	139.50	202.75	19.1	59.0

Table 6. Charpy V-Notch Properties of Fully Heat Treated Type 431 Test Material Subjected to Intervening Quench Delays. Results from Longitudinal Test Specimens Heat Treated and Then Ground to Finished Dimensions Before Testing (Average of 2 Specimens)

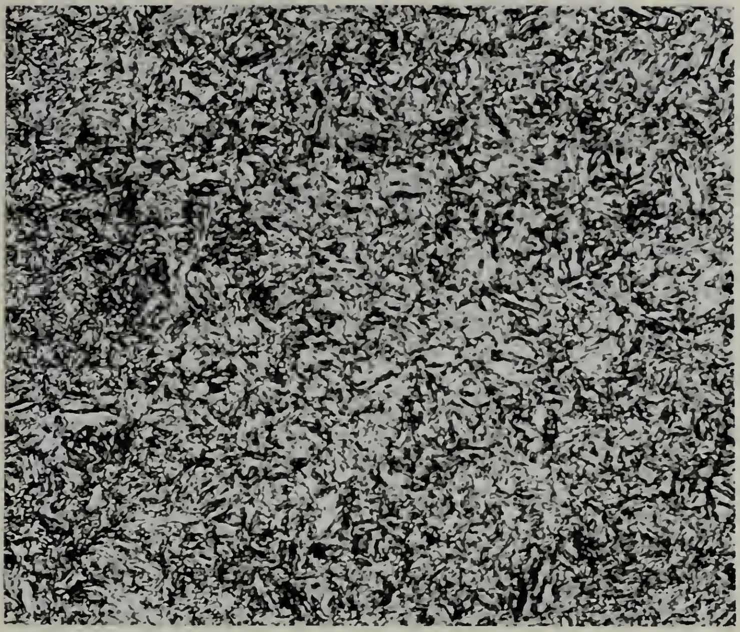
Quench Delay, Sec.	Charpy V-Notch, Ft.lbs Room Temperature	- 40° F
1	46.7	28.3
9	46.5	29.3
15	47.3	29.0
30	49.0	26.5
60	49.3	25.3



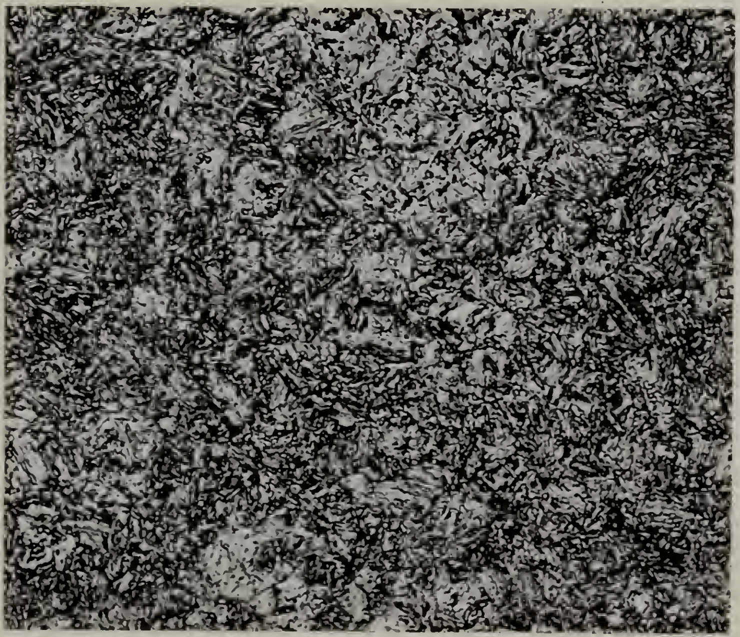
Longitudinal

Transverse

Figure 1. Inclusion content of the test steel. Unetched. X 500

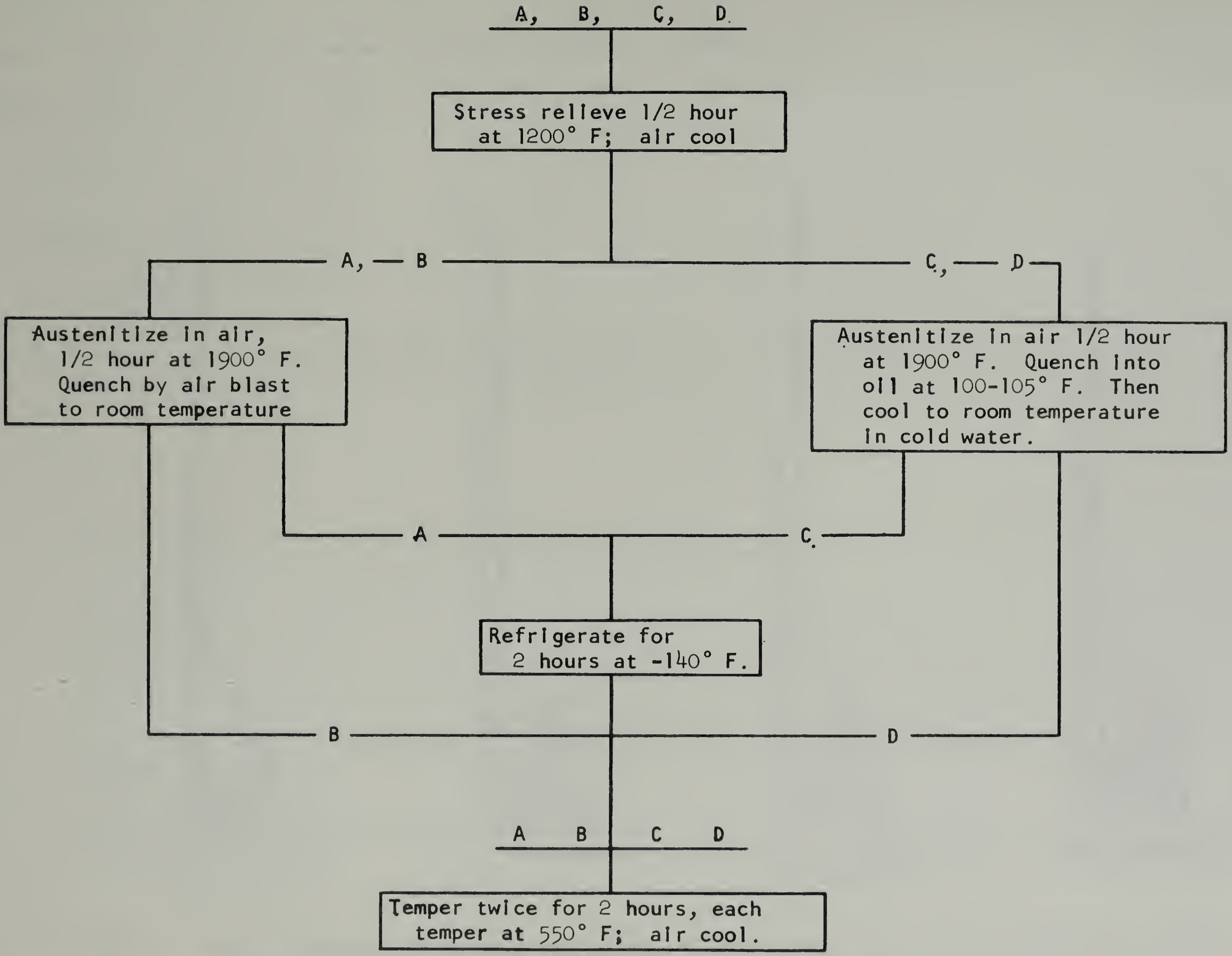


Longitudinal

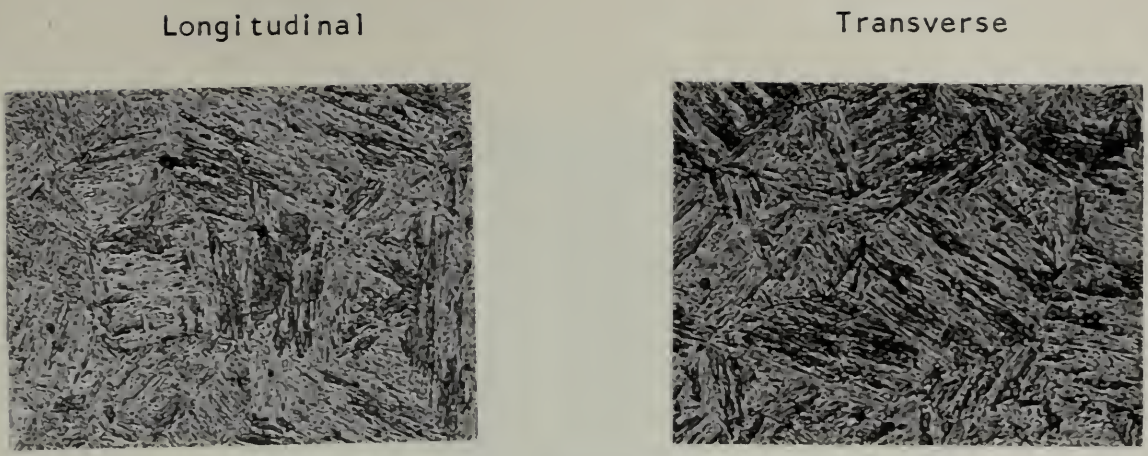


Transverse

Figure 2. Microstructure of the test steel in the as-received annealed condition. Structure consists of ferrite, decomposition products of austenite and some austenite. Etched with Vilella's reagent. X 500


A, B, C, D
Stress relieve 1/2 hour at 1200° F; air cool
A, — B
C, — D
Austenitize in air, 1/2 hour at 1900° F. Quench by air blast to room temperature
Austenitize in air 1/2 hour at 1900° F. Quench into oil at 100-105° F. Then cool to room temperature in cold water.
A
C.
Refrigerate for 2 hours at -140° F.
B
D
A B C D
Temper twice for 2 hours, each temper at 550° F; air cool.

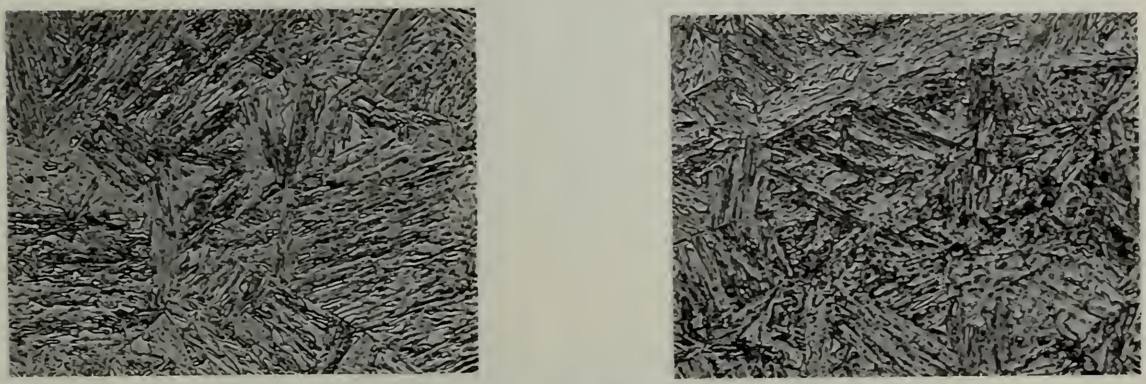
·Figure 3. Heat treating sequences for group A, B, C and D specimens.



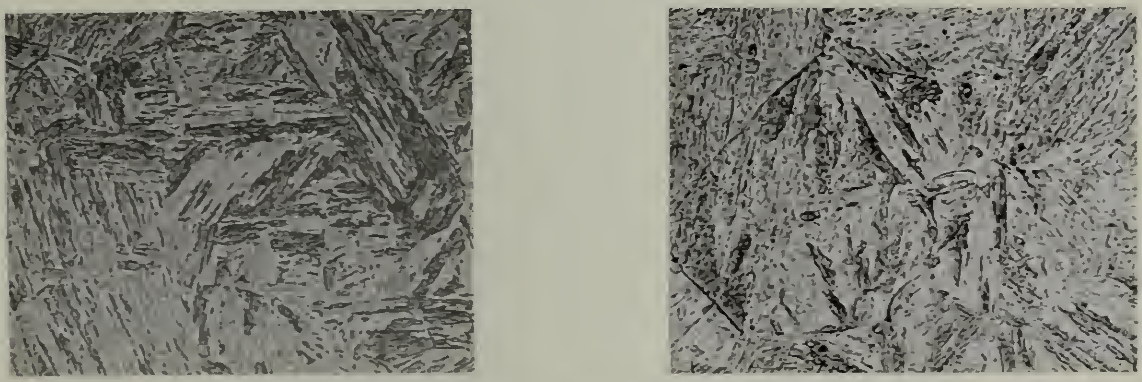
Longitudinal

Transverse

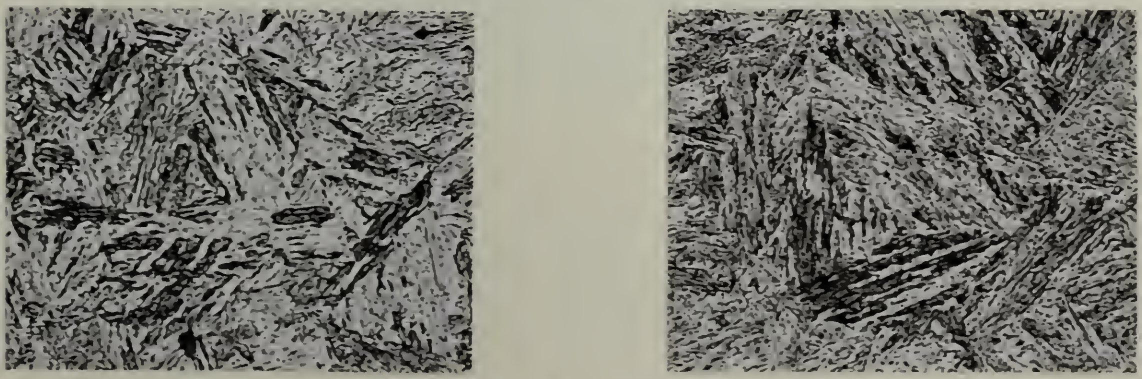
Air Hardened, Air Quenched, Refrigerated, Tempered



Air Hardened, Air Quenched, Tempered

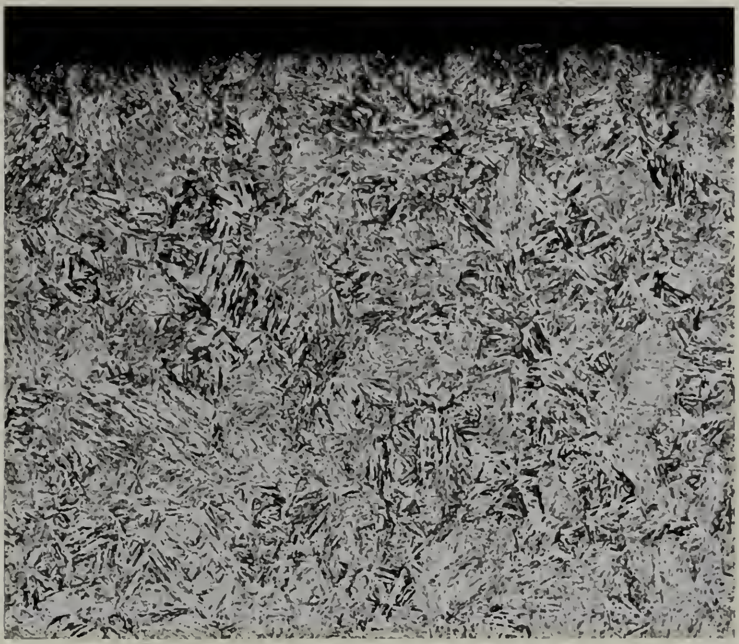


Air Hardened, Oil Quenched, Refrigerated, Tempered

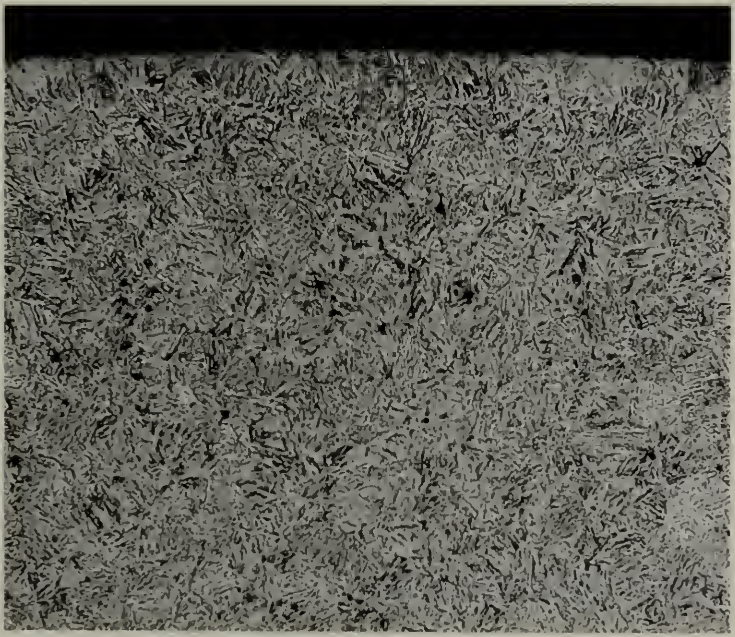


Air Hardened, Oil Quenched, Tempered

Figure 5. Microstructures of the test steel diversely heat treated to obtain a tensile strength of 200 Ksi. Etched with Vilella's reagent. X 500

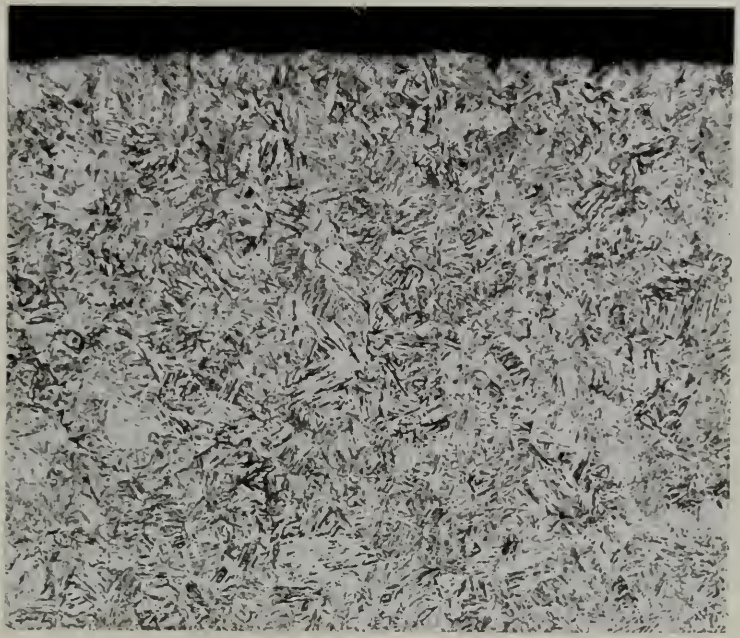


Air, Dew Point -30° F

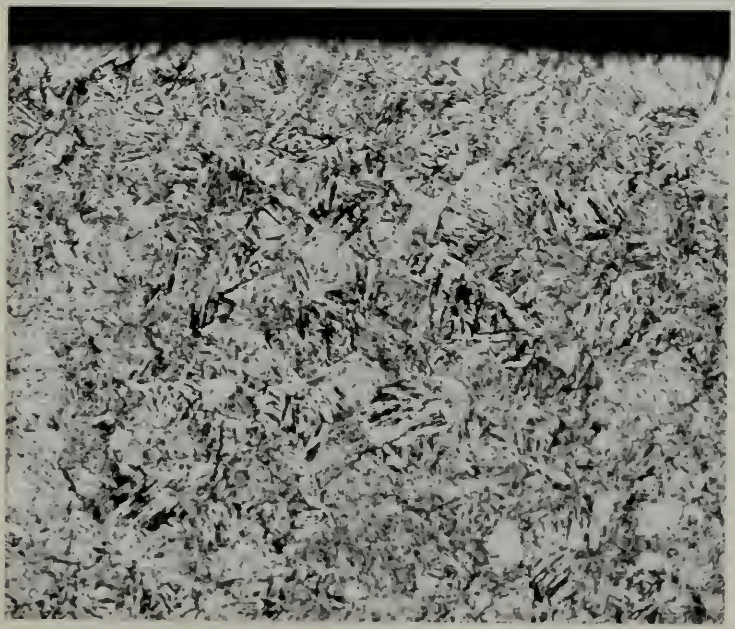


Air, Dew Point 70° F

Figure 6. Microstructures adjacent to surface of test steel hardened from air, dew points -30° F and 70° F. Transverse sections. Etched with Vilella's reagent. X 100

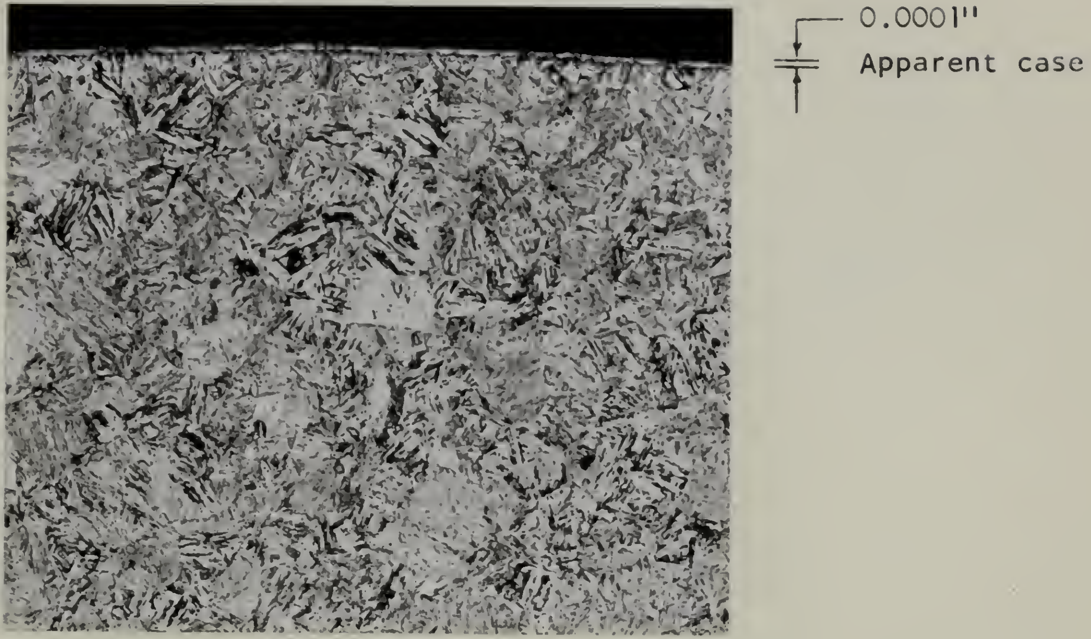


Argon, Dew Point -76° F

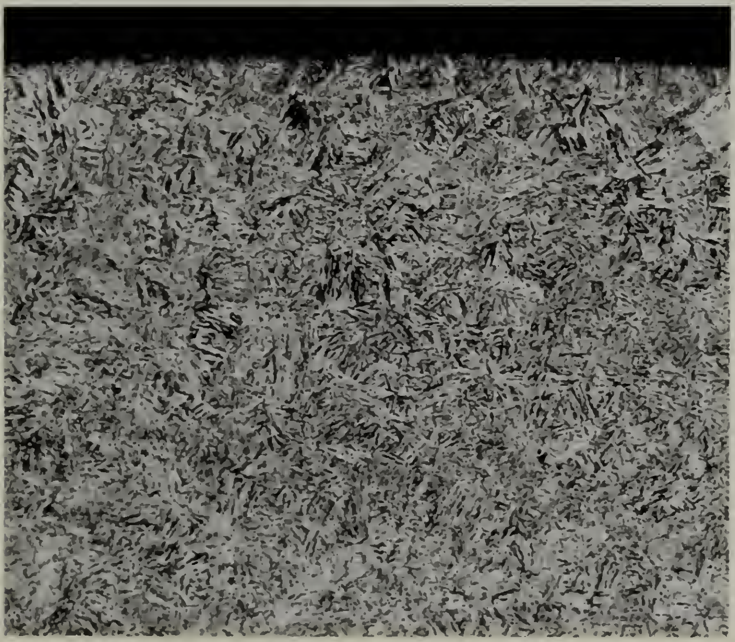


Argon, Dew Point -38° F

Figure 7. Microstructures adjacent to surface of test steel hardened from argon, dew points -76° F and -38° F Transverse sections. Etched with Vilella's reagent. X 100

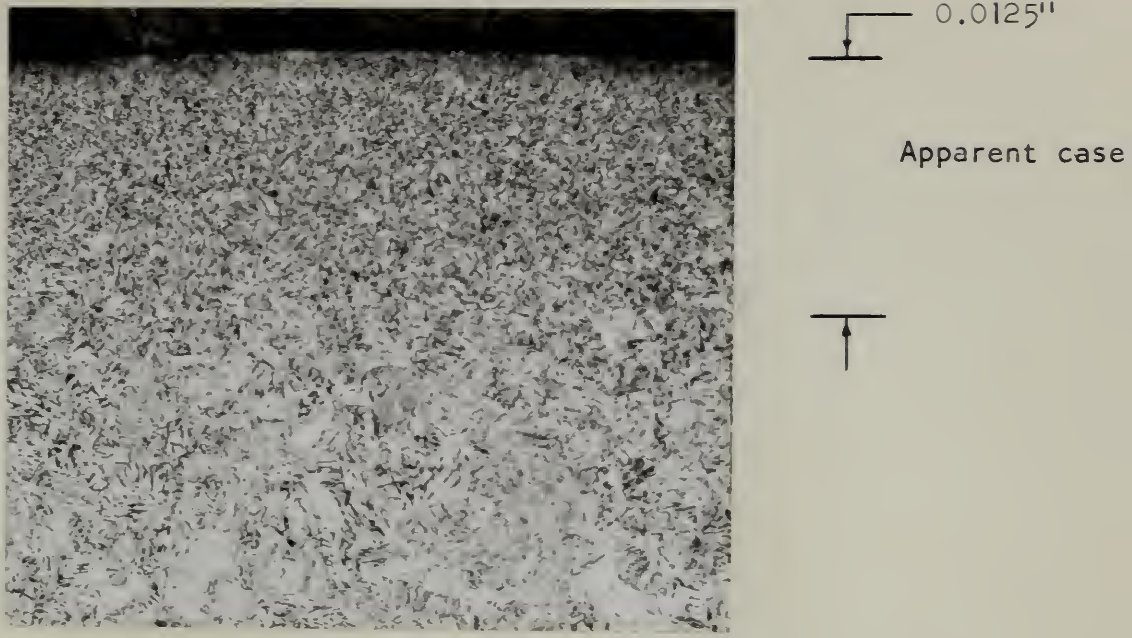


Dissociated Ammonia, Dew Point -59° F

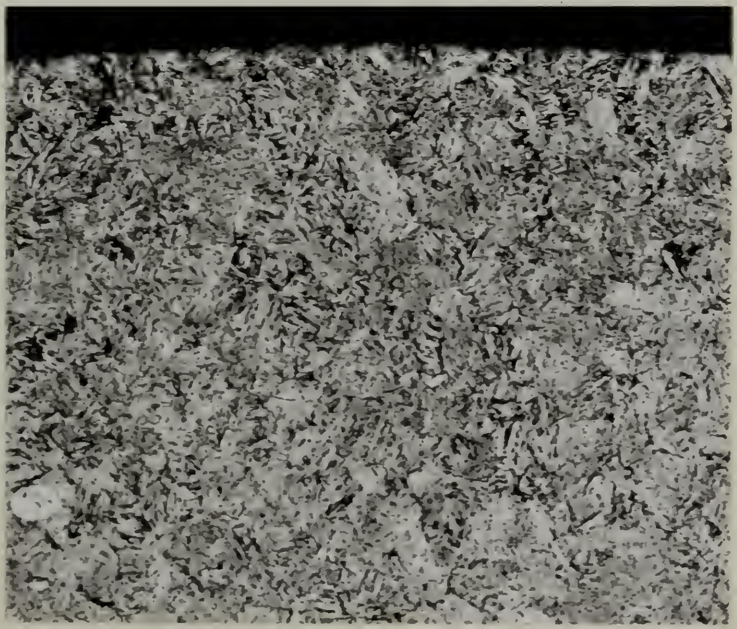


Dissociated Ammonia, Dew Point 24° F

Figure 8. Microstructures adjacent to surface of test steel hardened from dissociated ammonia, dew points - 59° F and 24° F. Transverse sections. Etched with Vilella's reagent. X 100



Endothermic Atmosphere, Dew Point 13° F



Endothermic Atmosphere, Dew Point 72° F

Figure 9. Microstructures adjacent to surface of test steel hardened from endothermic atmosphere, dew points 13° F and 72° F. Transverse sections. Etched with Vilella's reagent. X 100

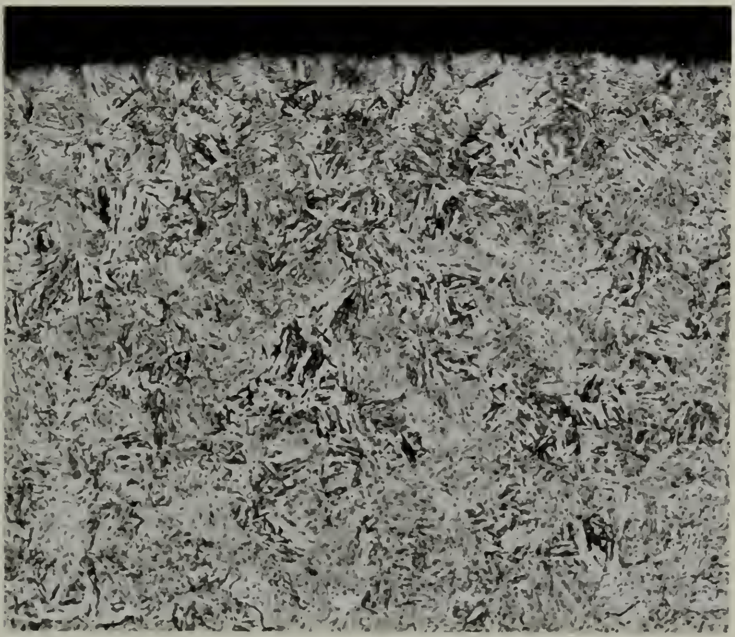
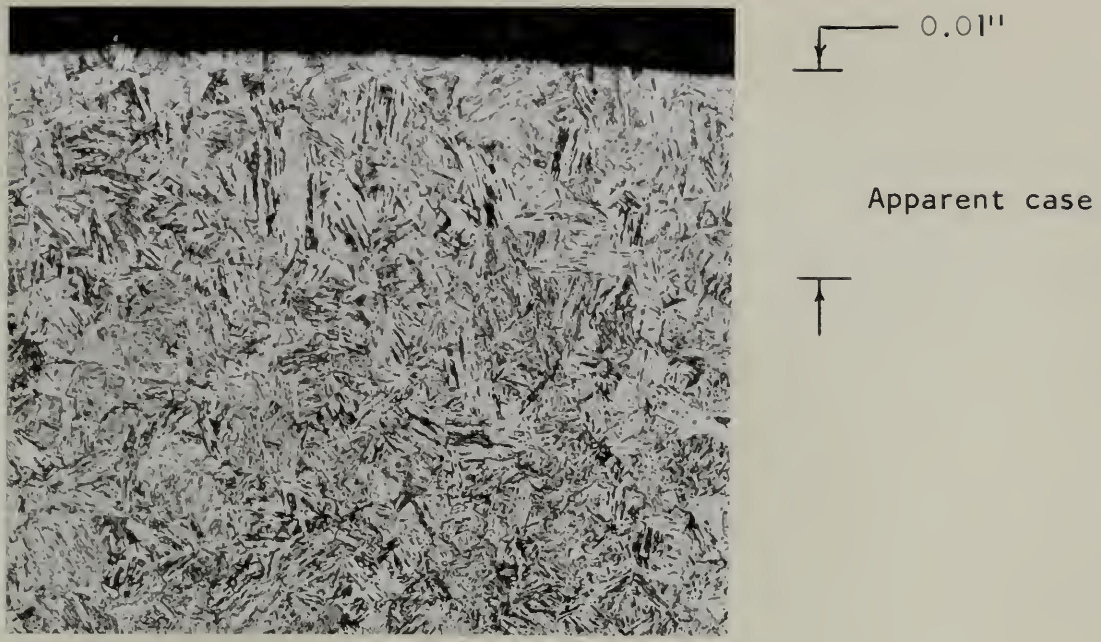
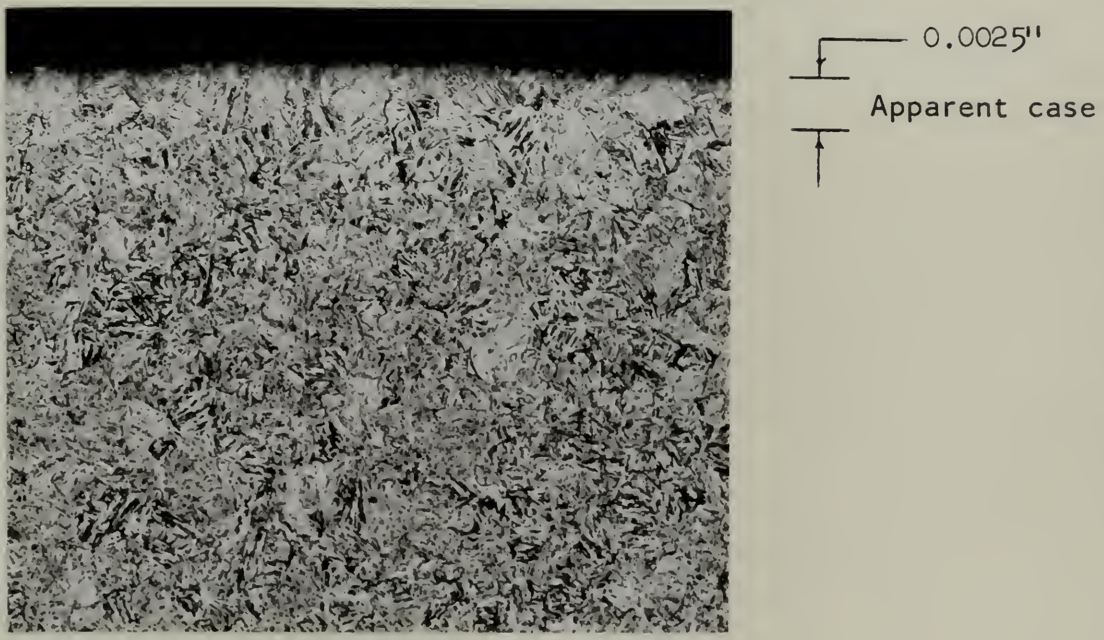


Figure 10. Microstructure adjacent to surface of test steel hardened from exothermic atmosphere, dew point 100° F. Transverse section. Etched with Vilella's reagent. X 100

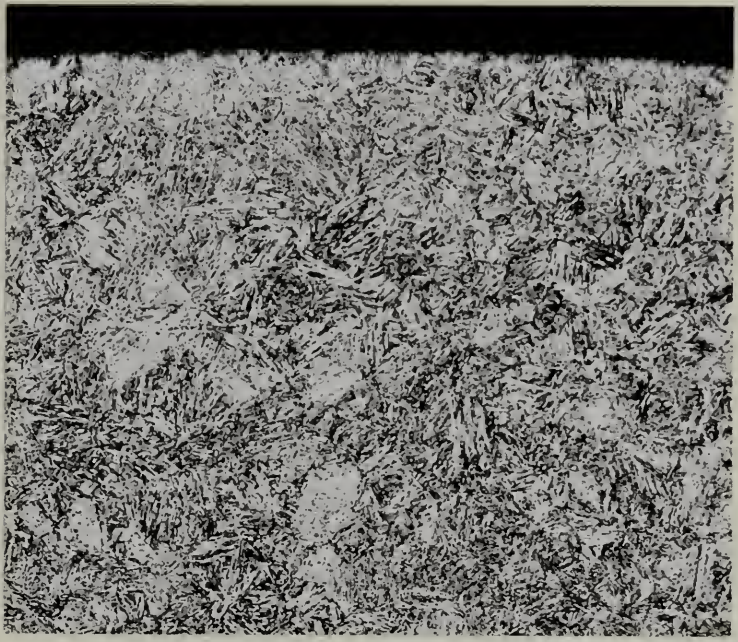


Hydrogen, Dew Point -87° F

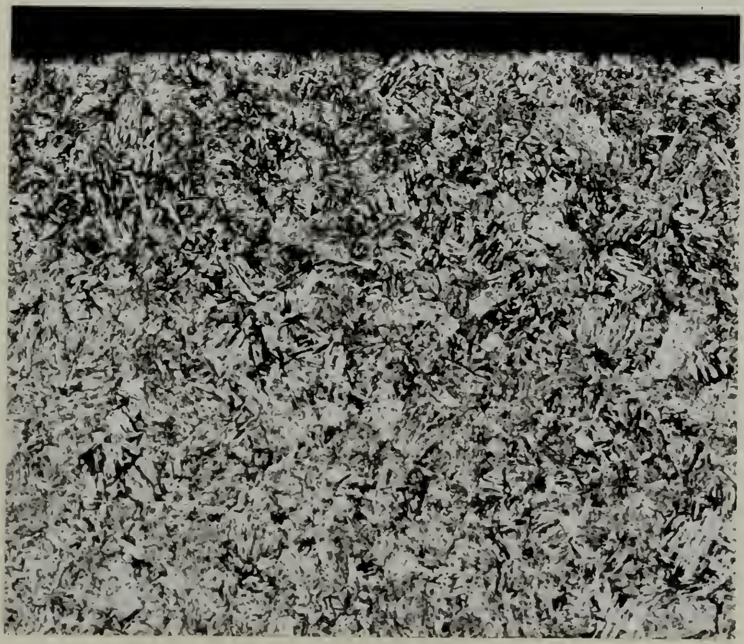


Hydrogen, Dew Point -17° F

Figure 11. Microstructures adjacent to surface of test steel hardened from hydrogen, dew points -87° F and -17° F. Transverse sections. Etched with Vilella's reagent. X 100



Nitrogen, Dew Point -80° F



Nitrogen, Dew Point -18° F

Figure 12. Microstructures adjacent to surface of test steel hardened from nitrogen, dew points -80° F and -18° F. Transverse sections. Etched with Vilella's reagent. X 100

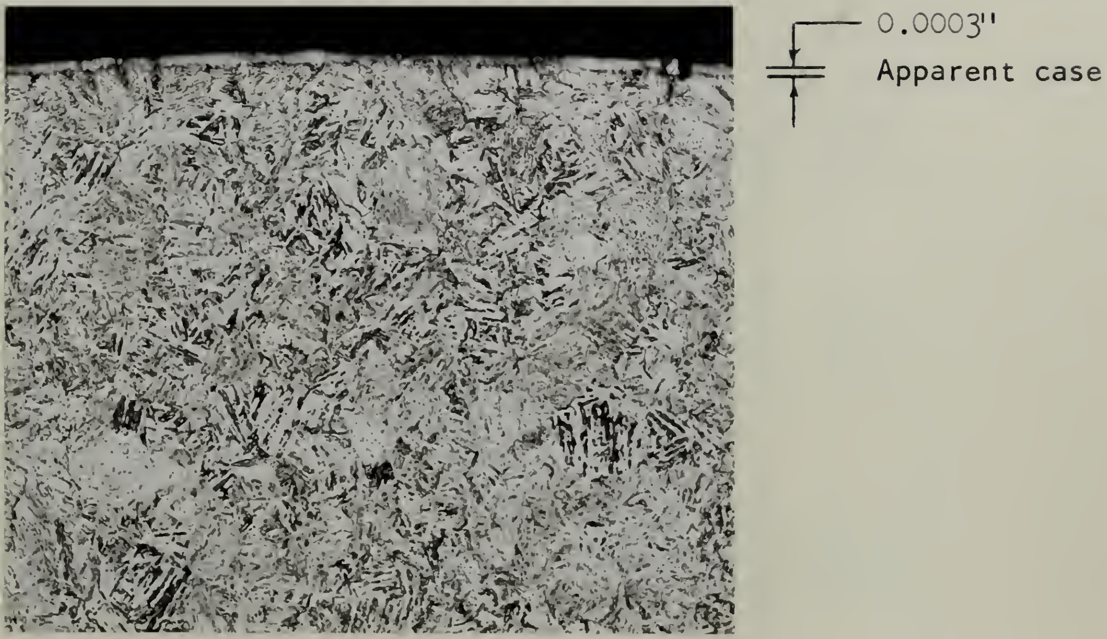


Figure 13. Microstructure adjacent to surface of test steel hardened from vacuum. Transverse section. Etched with Vilella's reagent. X 100

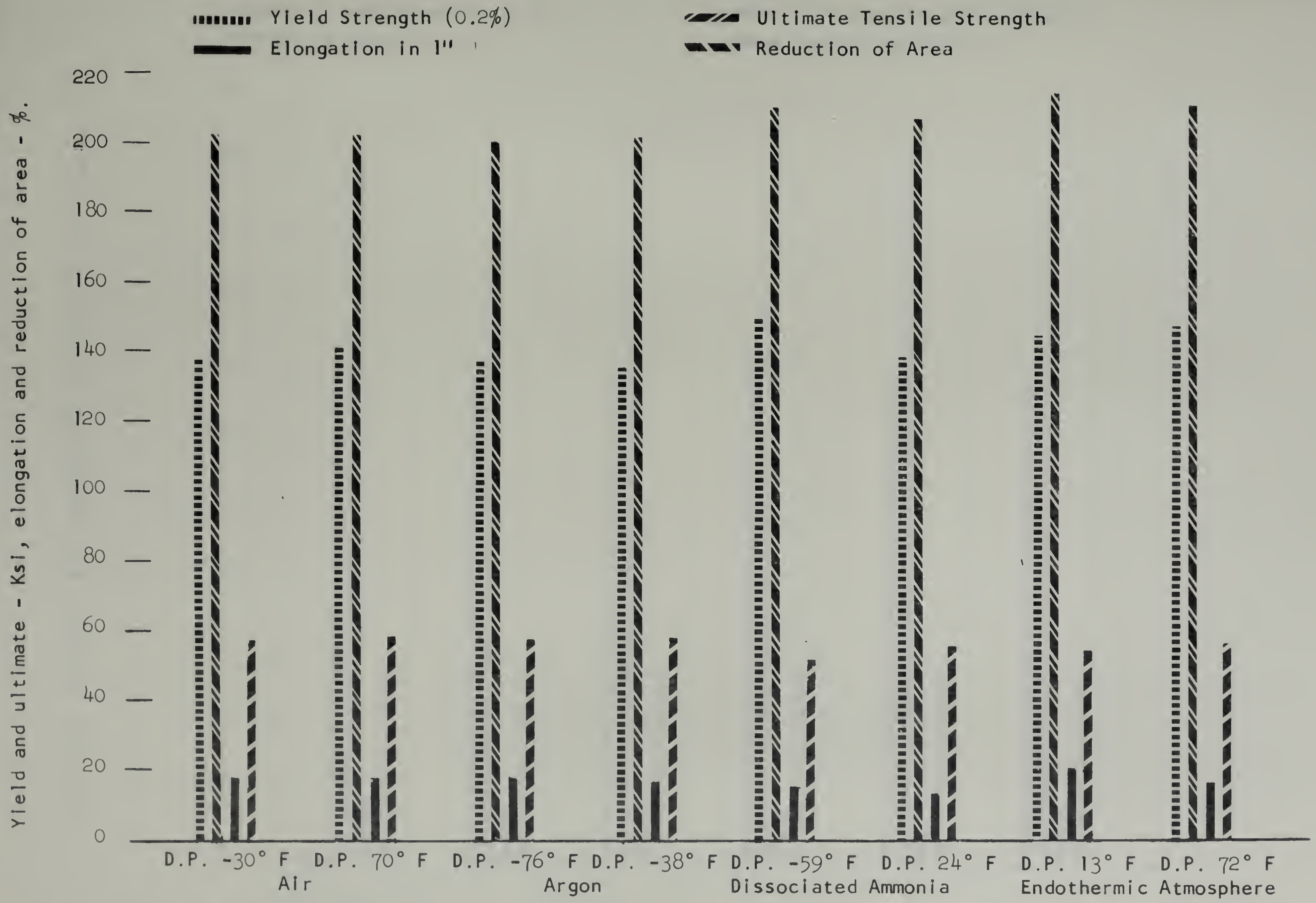


Figure 14. Mechanical properties of type 431 steel finish machined and austenitized in various media. Stress relieved 1/2 hr at 1200° F, austenitized - 30 min. at 1900° F, oil quenched, double tempered 2 hours at 550° F.

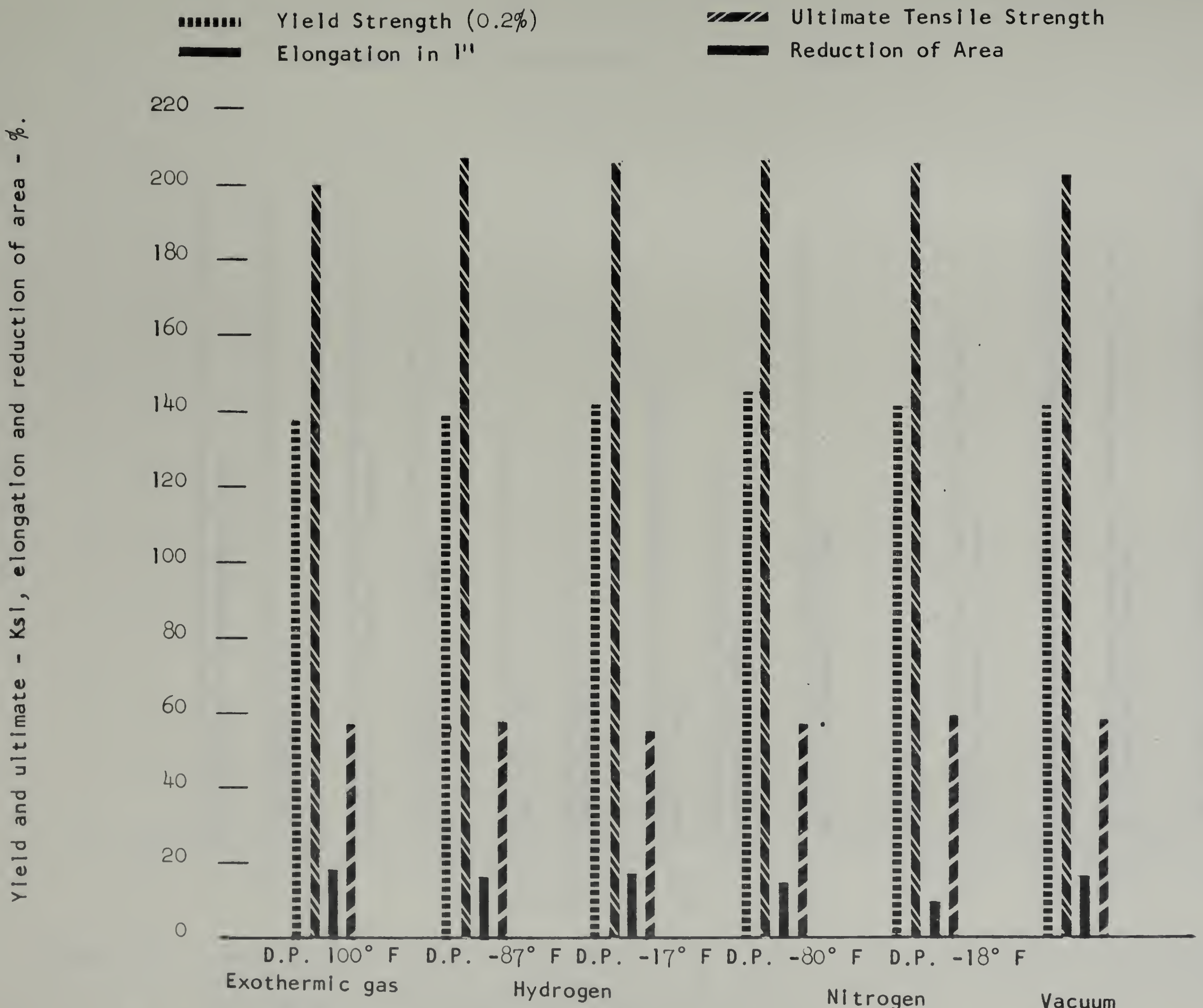


Figure 15. Mechanical properties of type 431 steel finish machined and austenitized in various media. Stress relieved 1/2 hr at 1200° F, austenitized - 30 min. at 1900° F, oil quenched, double tempered 2 hours at 550° F.

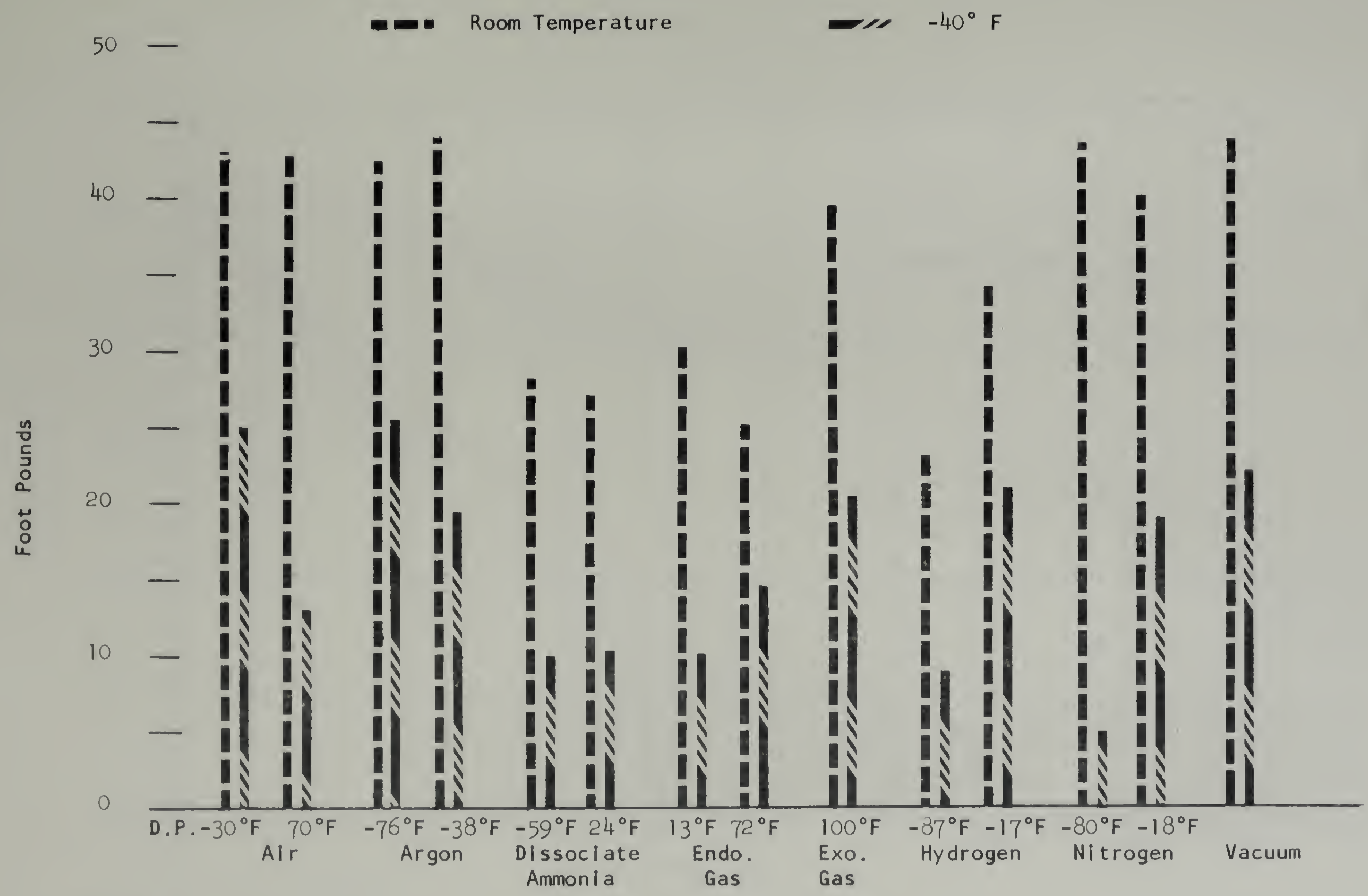


Figure 16. Charpy V-notch impact properties of type 431 steel finish machined and austenitized in various media. Stress relieved 1/2 hr at 1200° F, austenitized 30 min. at 1900° F, oil quenched, double tempered 2 hours at 550° F.

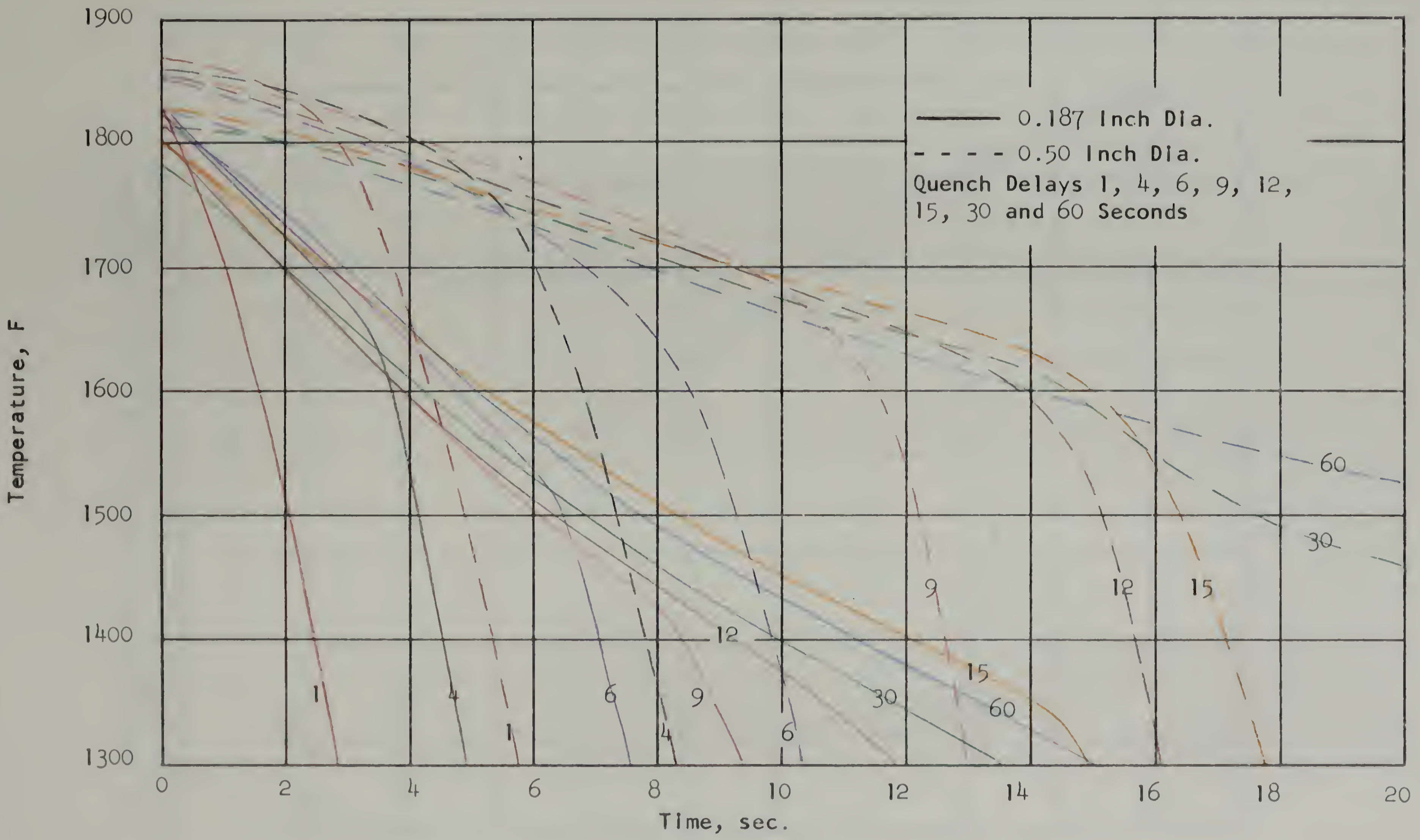


Figure 17. Characteristics of 0.187 inch and 0.050 inch diameter type 431 stainless steel specimens cooling from austenitizing temperature (1900° F), with intervening quench delays, to 1300° F.

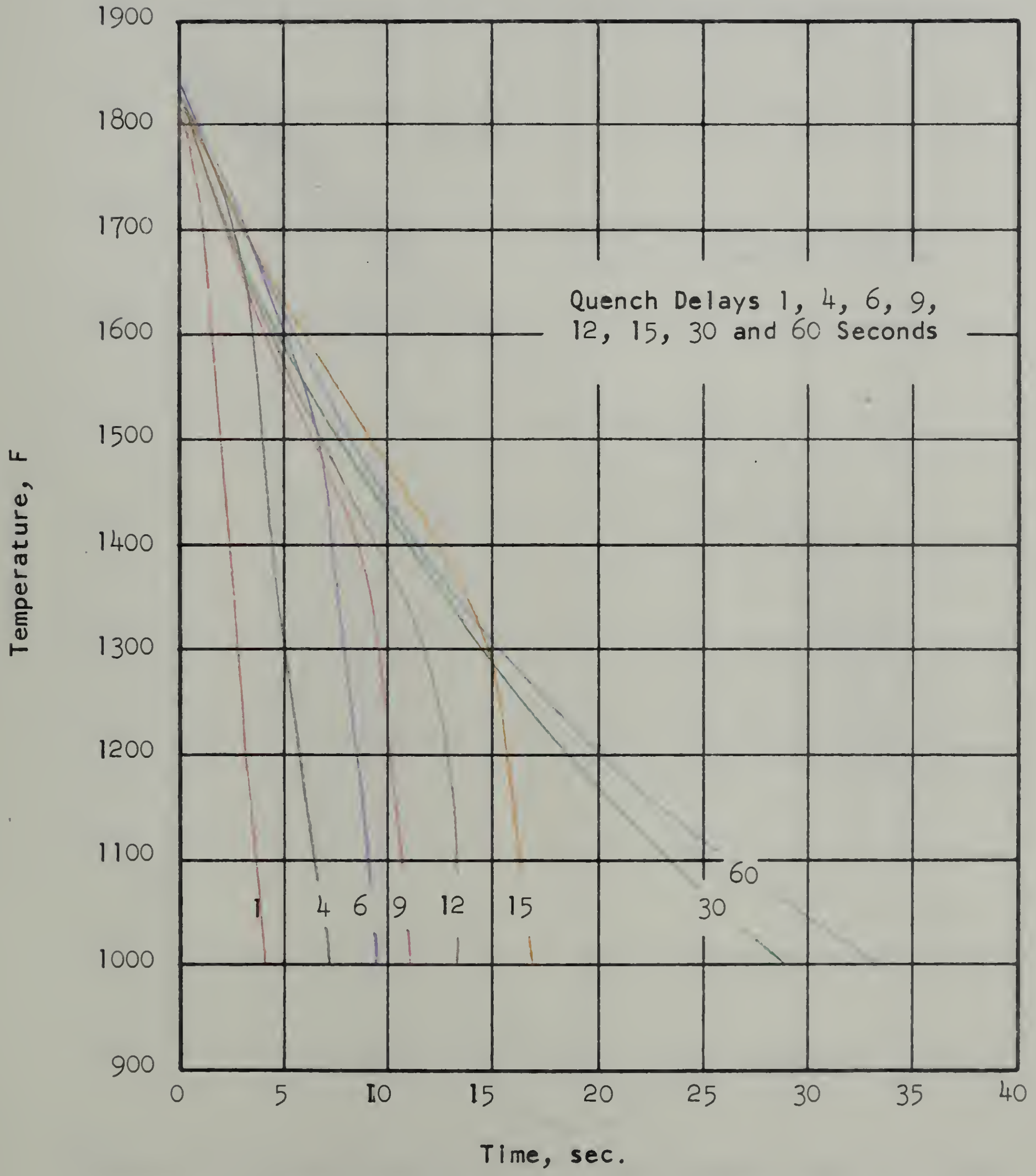


Figure 18. Characteristics of 0.187 inch diameter type 431 stainless steel specimens cooling from austenitizing temperature (1900° F), with intervening delays, to 1000° F.

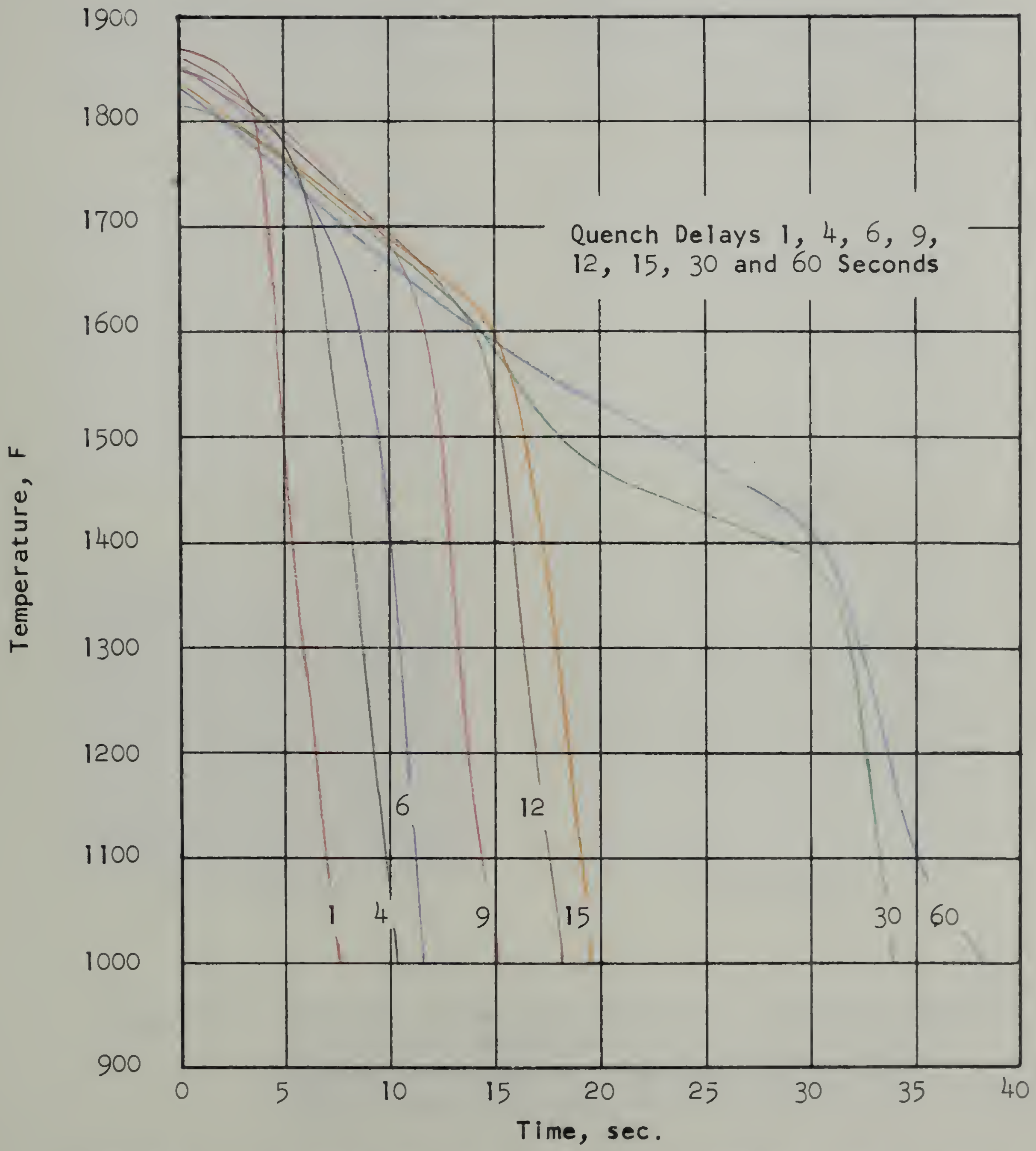
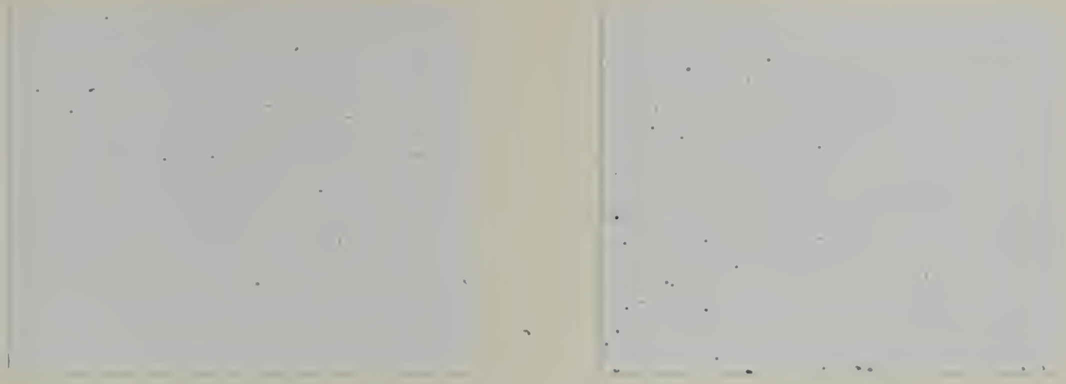
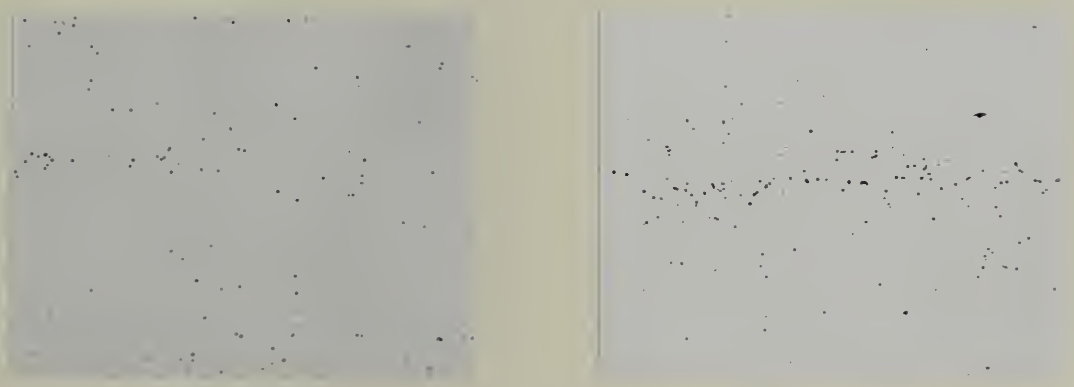


Figure 19. Characteristics of 0.50 inch diameter type 431 stainless steel specimens cooling from austenitizing temperature (1900° F), with intervening delays, to 1000° F.



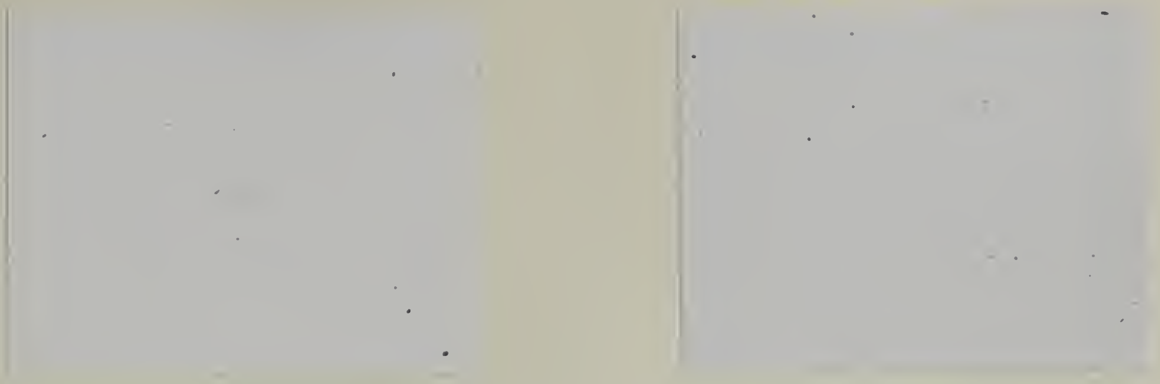
1 second 4 seconds

9 seconds 12 seconds



30 seconds 60 seconds

Figure 20. Carbides in the test steel; air hardened, quenched in oil after delays of 1, 4, 9, 12, 30 and 60 seconds and tempered. Section diameter 0.187 inch. Etched electrolytically with sodium cyanide. X 500

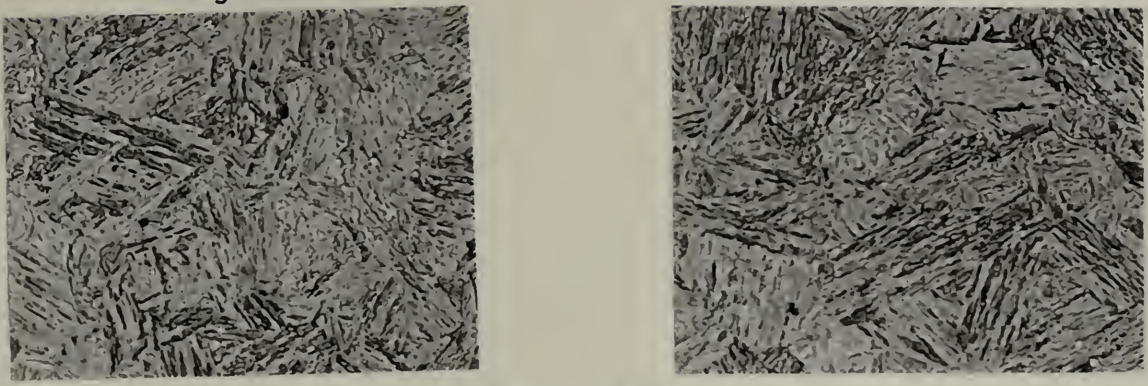


1 second 4 seconds

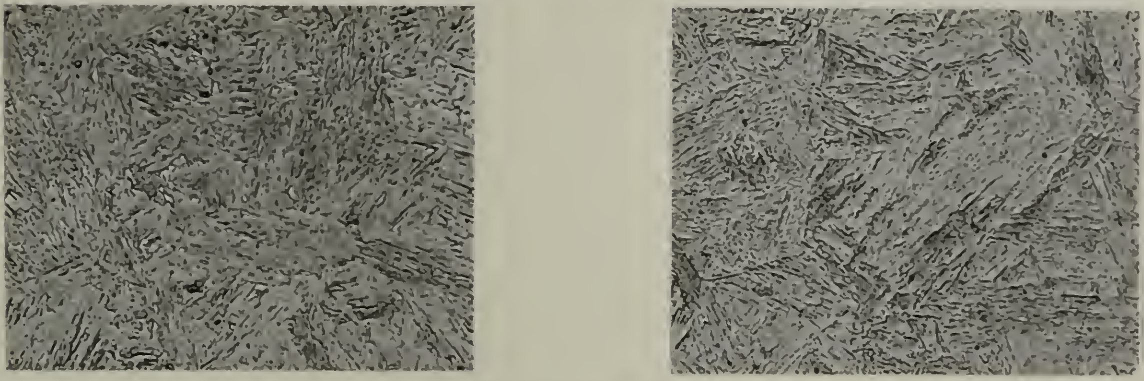
9 seconds 12 seconds

30 seconds 60 seconds

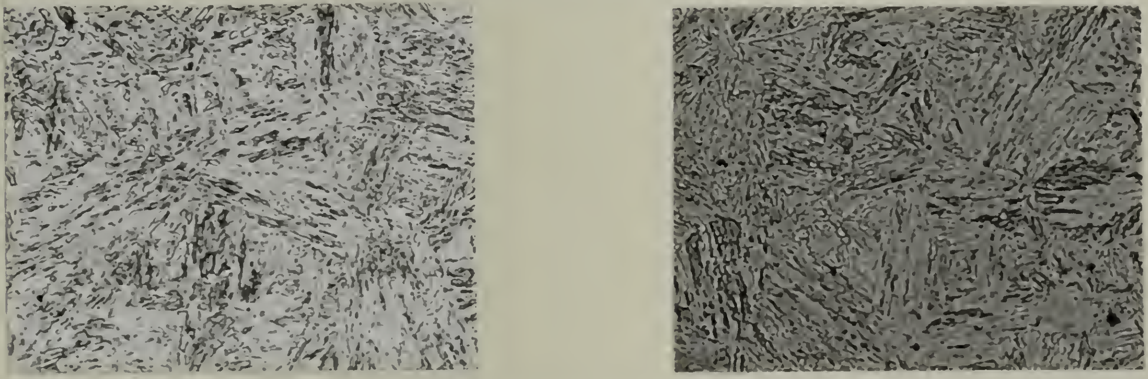
Figure 21. Carbides in the test steel; air hardened, quenched in oil after delays of 1, 4, 9, 12, 30 and 60 seconds and tempered. Section diameter 0.50 inch. Etched electrolytically with sodium cyanide. X 500



1 Second Delay

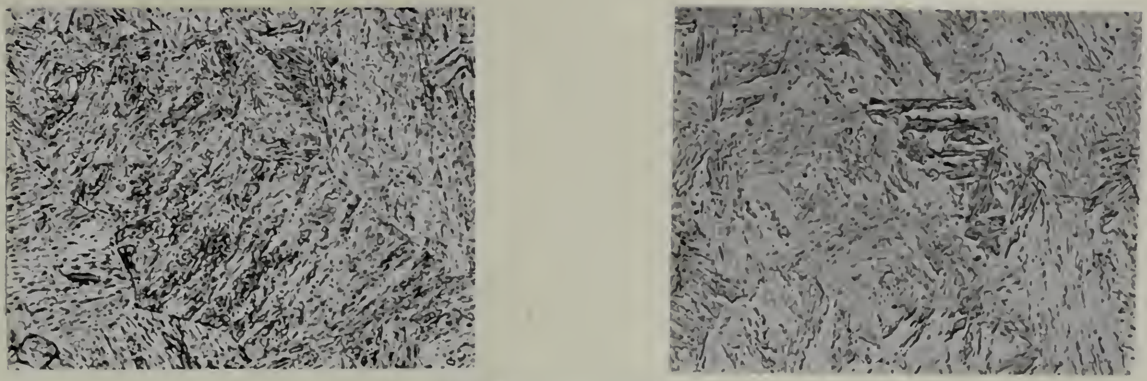


4 Second Delay



9 Second Delay

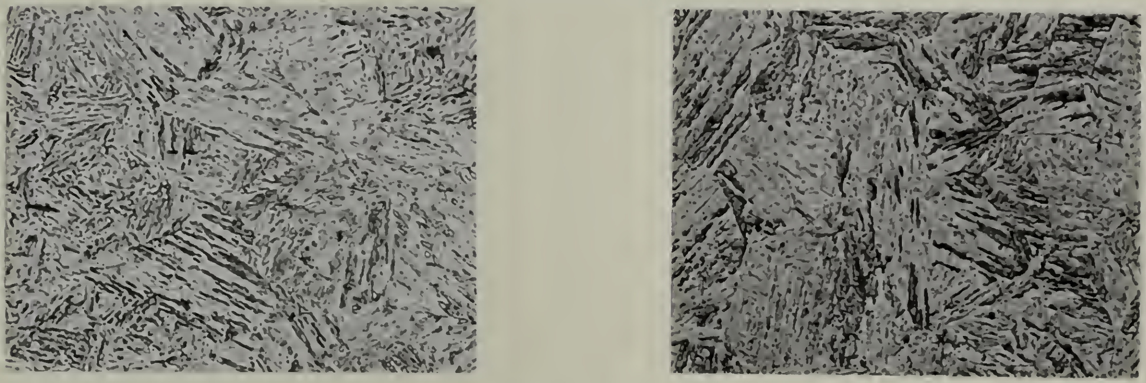
Figure 22. Microstructures of the test steel; air hardened, quenched in oil after delays of 1, 4 and 9 seconds and tempered. Section diameter 0.50 inch. Etched with Vilella's reagent. X 500



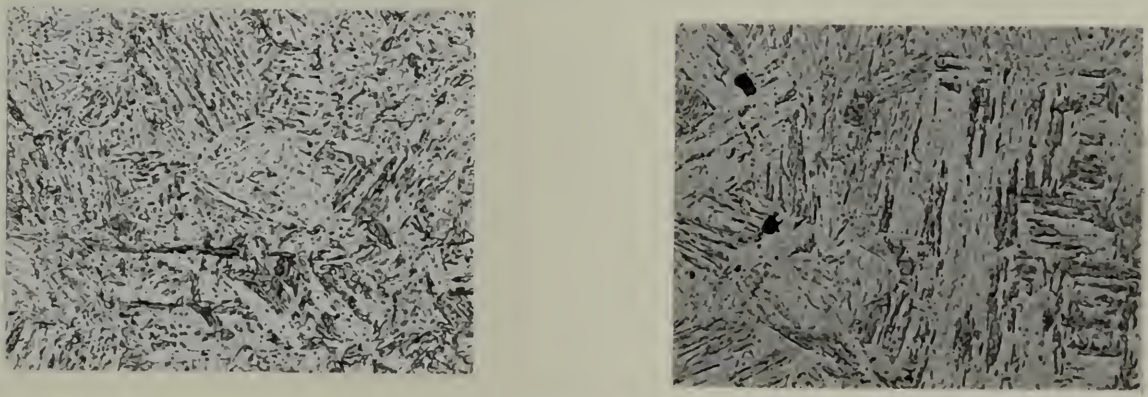
Longitudinal

Transverse

12 Second Delay



30 Second Delay



60 Second Delay

Figure 23. Microstructures of the test steel; air hardened, quenched in oil after delays of 12, 30 and 60 seconds and tempered. Section diameter 0.50 inch. Etched with Vilella's reagent. X 500

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